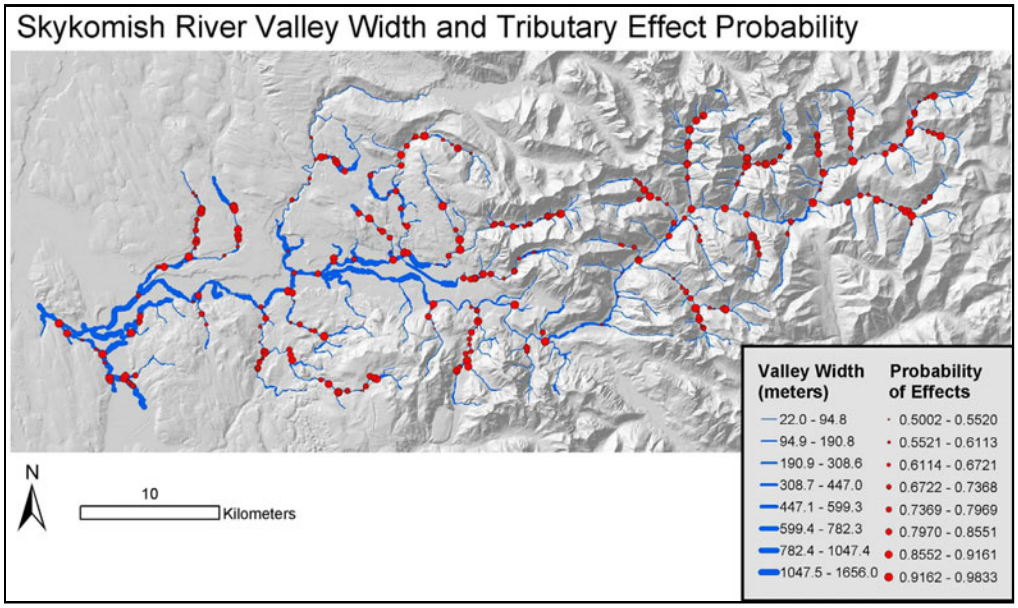

Figure 10. Skykomish valley segment and confluence map.

Network and Tributary Junction Characteristics

Similar to the methods used for the Snoqualmie River, a logistic model (Chapter 2, Figure 5) was used to predict the tributaries that could impact the morphology of the Skykomish River between Sunset Falls and the confluence of the Snoqualmie River. Although the probability of confluence effects greater than or equal to 0.5 are plotted in Figure 10, we evaluate only those with a probability greater than or equal to 0.75, as discussed previously. Downstream of Sunset Falls, these tributaries included the North Fork Skykomish (P = 0.95), Wallace Creek (P = 0.87), Sultan River (P = 0.90), Woods Creek (P = 0.84), and the Snoqualmie River (P = 0.97) (Table 2). Woods Creek basin contains numerous wetlands and lakes, and sediment recruitment to the Skykomish is minimal (Haring 2002). Consequently, Woods Creek is removed from the list of tributary basins predicted to have significant tributary junction effects.

The tributaries predicted to have a morphological effect in the Skykomish River (e.g., Figure 10) could influence the spatial distribution of spawning Chinook by providing coarser substrate, creating a knick point in the river altering channel gradients and increasing hyporheic flow, and creating more side channels and pools. The spacing between the tributary junctions predicted to have morphological effects ($P \geq 0.75$) from upstream to downstream is 13.9 mi (22.2 km), 1.3 mi (2.1 km), and 13.9 mi (22.2 km). The average distance between the predicted geomorphically significant tributaries is 9.7 mi (15.5 km). Two of the principal tributaries (Sultan and Wallace) are less than 1.3 mi (2.1 km) apart, and hence their effects likely overlap. If these tributaries are combined into a single feature, then the average spacing among the three tributary systems is 13.9 mi (22.2 km). Consequently, we would predict that the large scale structure of spawning Chinook habitat includes tributary confluences in the Skykomish River that have a scale of variation that averages 15 to 30 km (i.e., distance separating concentrations of spawning habitat). However, an additional interpretation is that the Wallace and Sultan systems (which are less than 2 km apart), in combination, are the major supplier of spawning size substrate between the upper canyon segment (below Sunset Falls) and the Snoqualmie River. Hence, spawning Chinook may be concentrated at the loci of gravel recruitment (Sultan and Wallace systems) and taper off downstream with declining gravel supply. Although gravel substrate enters the Snoqualmie River, converting the sand bed river (above the confluence) to a gravel bed channel, the infusion of gravel substrate tapers off approximately 3 to 4 miles below the Snoqualmie confluence.

Other Data

There is limited information on sediment transport potential and channel response in Collins and Dunne (1987, as cited in Gersib et al. 1999), including estimated basin sediment yields and identification of variations in sediment storage conditions in the lower mainstem of the Skykomish River. In addition, the Washington Stream Catalog (Williams et al. 1975) provides an overview of physical conditions within the major tributaries of the lower river. For example, sediment supply to the mainstem from Woods Creek is minimal because of the basin's numerous lakes and wetlands.

Lower Green River

General River Basin Characteristics

The Green River, located in the southern portion of King County, has a drainage area of approximately 1,000 km^2. The study segment is located below Howard Hanson dam (closed in 1961), and it extends downstream to the historical confluence with the White River (RM 31 to 32) and contains two major tributaries, the Newaukum and Big Soos creeks (Figure 11). Downstream of the reservoir the river flows through the 13 mi (21 km) Green River Gorge. The downstream section of the gorge contains Flaming Geyser State Park. Geologic materials along the lower segment of the Green River include sedimentary rocks (sandstone with interbedded shales) of the Tertiary Puget Group. The Green River Gorge, however, is composed mostly of volcanic rocks. Gravelly to sandy glacial outwash terraces flank much of the river. Maximum channel width (includes unvegetated bars) ranges from 150 to 1,200 ft (45 to 370 m), and channel gradients range from 0.08% downstream to 0.53% below the dam (Figure 12).

Figure 11. Green River location map.

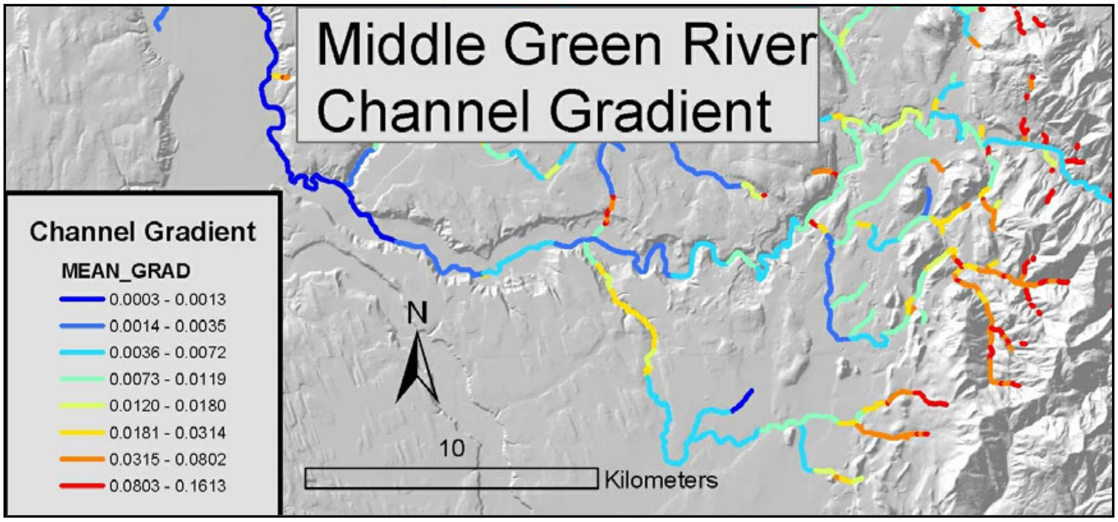

Figure 12. Green River gradient map.

Valley Segment Characteristics

There is little variation in valley width other than the Green River Gorge located at the upper section of the study reach downstream of the Howard Hanson dam (Figures 6 and 13 and Perkins 2000). The upstream and downstream mouths of the canyon are located, respectively, at RM 57.6 and RM 45.3.

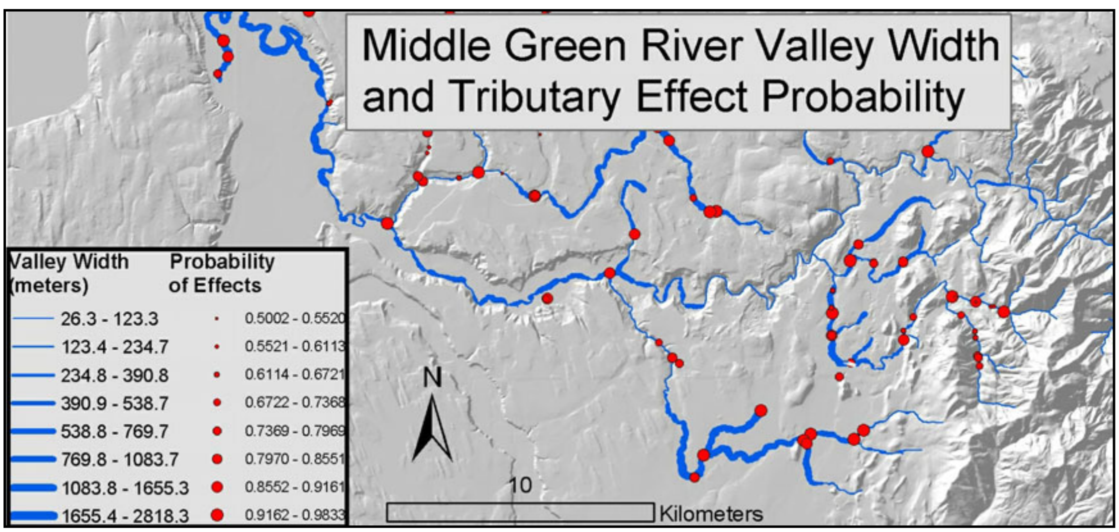

Figure 13. Green River valley segment and confluence map.

Network and Tributary Junction Characteristics

The logistic regression model (Chapter 2, Figure 5) was used to predict whether tributaries in the Lower Green River could trigger confluence effects that impact spawning Chinook salmon. Again, only those tributaries with greater than or equal to a probability of 0.5 are mapped in Figure 13. Using a probability threshold of $P \geq 0.75$, only two tributaries are predicted to have significant morphological effects, namely Newaukum and Big Soos creeks (Table 2). Most of the sediment production in Big Soos Creek is trapped in wetlands or in the low-gradient valley bottom in the lower end of the watershed (Perkins 2000). Nevertheless, Big Soos Creek is included in our analysis since it does supply modest amounts of bedload to the Green River (Perkins 2000). In addition, even though the White River was diverted from the Green River in 1906 (Perkins 2000), the historical confluence of the White River located at approximately RM 31 was included in the analysis because it created a large alluvial fan (at the confluence with the Green River) that continued to impact the river, at least in the late 1970s (Dunne and Dietrich 1978). However, the White River drainage area of 1,225 km^2 is 1.6X the drainage area of the Green River (755 km^2). Hence, the Green River is a tributary to the White River (presently called the Green River since the White River was diverted in 1906) and has a tributary to mainstem drainage area ratio of 0.6, which is equivalent to a P of 0.91.

Other Data

The Green River (below the Howard Hanson dam) has been the subject of several studies including 1) sediment transport and channel dynamics (Dunne and Dietrich 1978), 2) channel migration (Perkins 1993), and 3) geomorphic evaluation of gravel placement (WEST Consultants, Inc. 2000; Perkins 2000). Perkins (1993) documented the history of channel migration on the Lower Green River, which revealed two principle zones of channel migration, upstream and downstream of Newaukum Creek and downstream of Big Soos Creek. Perkins (1993) concluded that the highest channel meandering was related to absence of revetments and wide valley floors. However, high rates of channel meandering also have been associated with tributary confluences (Church 1983), and the high rates of meandering in the Green River are both spatially associated with confluences. The uppermost area (RM 40 to 42) is located in the immediate vicinity of Newaukum Creek, and the lowest area of high channel meandering (RM 32 to 34) is associated with Big Soos Creek. More importantly, the area is located immediately upstream of the historical White River confluence, where a large alluvial fan has been detected (Dunne and Dietrich 1978).

The Perkins (2000) study also documented three large landslides in glacial outwash deposits. One of the slides located in the Green River Gorge (RM 42.6) created a gravel deposition area below it for approximately 2.5 km. The other slides were also considered large gravel sources, particularly given that Howard Hanson Dam is denying gravel supply to the lower portion of the river, including a major landslide located at RM 49.7 (Perkins 2000).

Based on the network model and information from previous studies, we predict that spawning habitat for Chinook should have a spatial scale of variation that reflects large tributaries (including the historical White River), landslides, and canyon mouths. The scale of variation among the different large-scale features ranges from 1.9 mi (3 km) to 7.9 mi (12.6 km) and averages 4.2 mi (6.7 km), indicating a spatial structure on the order of 3 to 10 km. Smaller scale variation in spawning habitats was not verified during this study but may be on the order of 1,000 ft (0.3 km), a scale reflecting the pool-riffle spacing along the Lower Green River (Perkins 1993).

Lower Cedar River

General River Basin Characteristics

The Cedar River drains an area of 487 km^2. The river is approximately 50 miles long and can be divided into an upper basin that extends from the headwaters in the Cascade Mountains to the City of Seattle water diversion dam (Landsburg Dam at RM 22) and the lower basin that extends from Landsburg to Lake Washington. The rivers in the upper basin are typical steep mountain streams that drain into a large water supply reservoir (Chester Morse Lake). The mainstem river is confined in a narrow valley that extends downstream from the reservoir to several miles below the Landsburg Diversion Dam. The lower river flows through a low-gradient alluvial valley that is confined by steep bluffs. The lower basin has several small tributaries, including Rock, Peterson, Taylor, Madsen, and Molasses creeks (Figure 14). Channel gradients in the lower Cedar River range from 0.04% to 0.7% (Figure 15).

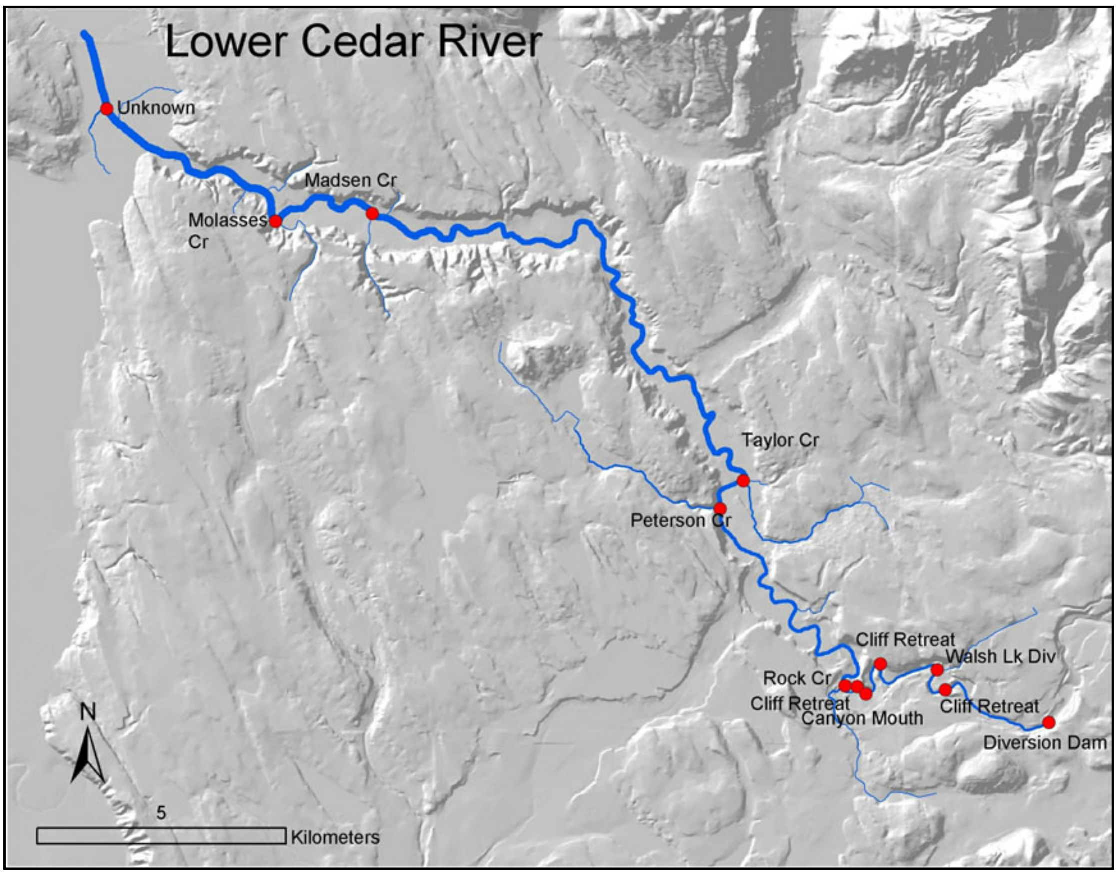

Figure 14. Cedar River location map.

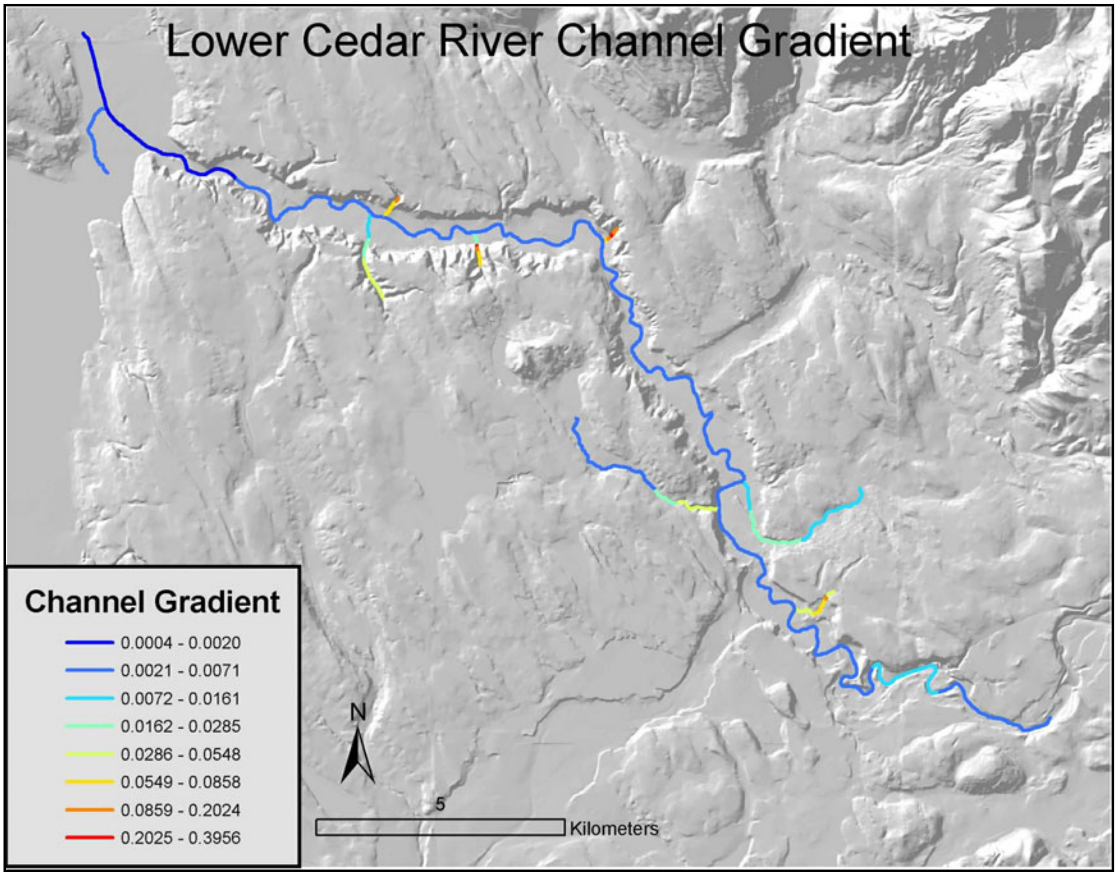

Figure 15. Cedar River gradient map.

Valley Segment Characteristics

The most prominent canyon in the Lower Cedar River occurs below Chester Morse Lake, and it terminates just upstream of Rock Creek (Figure 12). Within the canyon, a series of eroding cliffs (landslides) within gravelly glacial outwash are a major source of gravel to the Lower Green River. The prominent downstream mouth of the canyon is located at RM 18.6. The only other relatively minor valley constriction occurs between RM 9.2 and 10.3. Consequently, we predict that the canyon mouth, in conjunction with landslide-sources of gravel in the same area (see below), should influence the spatial structure of spawning Chinook salmon.

Network and Tributary Junction Characteristics

The logistic regression equation (Chapter 2, Figure 5) was used to predict the abundance and location of geomorphically significant tributary confluences along the Lower Cedar River. Although all confluences with a probability greater than or equal to 0.5 are shown in Figure 16, we considered only confluences with probability greater than or equal to 0.75, similar to the other three Puget Sound rivers.

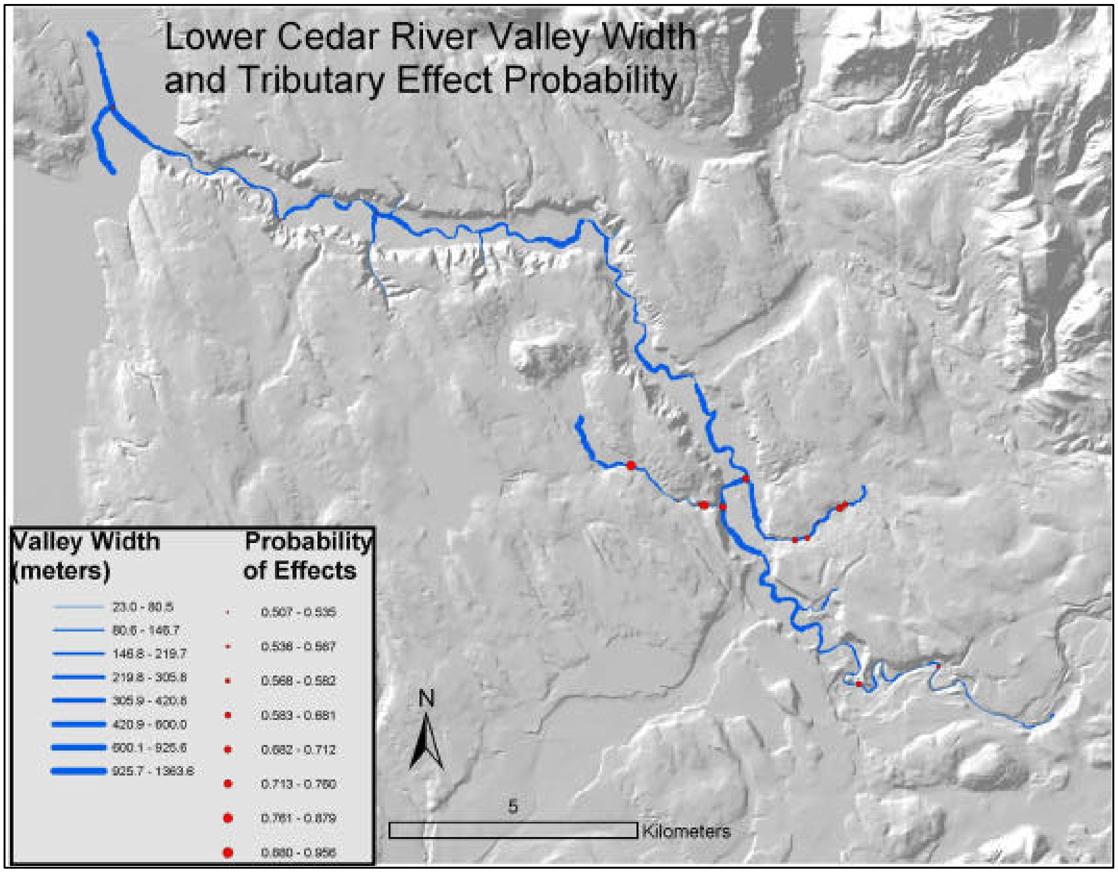

Figure 16. Cedar River valley segment and confluence map.

The network model revealed no tributaries along the Lower Cedar River greater than probability 0.75. However, a sediment budget constructed for the lower river revealed that Peterson (P = 0.01) (RM 14.4) and Rock (P = 0.66) Creeks (RM 18.4), and the Walsh Lake Diversion Ditch (RM 20.3) contributed modest amounts of bedload to the Lower Cedar River (Perkins Geoscience and R. H. Righellis, Inc. 2002). However, the total gravel supply below Landsburg from the three tributary sources was estimated at 800 cy/yr compared to landslide sources of gravel of 6,500 cy/yr. Consequently, we do not predict that Chinook spawning habitats will be structured by tributaries. However, we do predict that they should at least in part be structured by the canyon mouth at RM 18.6, in conjunction with landslide sources of spawning gravel (see below).

Other Data

A number of studies have evaluated various aspects of the Cedar River watershed, most prominently a gravel budget for the lower river (Perkins Geoscience and R. H. Righellis, Inc. 2002; Jones and Stokes 2002), a watershed analysis of the Cedar River basin (Foster Wheeler 1995), an analysis of instream flows (Cascade Environmental Services 1991), and a flood damage assessment (Golder Associates 2001). With respect to our analysis of the spatial structure of Chinook spawning habitat, the gravel budget of Perkins Geoscience and R. H. Righellis, Inc. (2002) is the most pertinent.

The locations of two major landslides in the upper portion of the Lower Cedar River are plotted in Figure 14. Landslides and cliff erosion at RM 18.4 and RM 19.3 (Figure 14) are located, respectively, 0.2 mi (0.3 km) upstream of the canyon mouth and 0.7 mi (1.1 km) downstream of the canyon mouth. Overall, landslides contribute 92% of the gravel size substrate to the Lower Cedar River below the dam, and the majority of that originates in the first 6 mi (9.6 km) of river below Landsburg (Perkins Geoscience and R. H. Righellis, Inc. 2002).

Based on the lack of geomorphically significant tributaries in the Lower Cedar River, we predict that a major concentration of spawning Chinook habitat will be organized around the prominent canyon mouth at RM 18.6 (i.e., the onset of a wider floodplain segment) and near the location of major sources of spawning gravel. A confounding factor is the dam at Landsburg, which blocks fish passage. This likely influences the location of spawning Chinook such that they may become concentrated at the first location of high quality habitat below the dam, namely the canyon mouth at RM 18.6. Other than the predicted concentration of Chinook spawning habitat near the canyon mouth and the landslides, the spatial structure of habitat should be governed by smaller scale features, such as meander wavelengths and perhaps log jams. The occurrence and scale of the smaller habitat features, however, were not determined during this analysis.

Predicted Structure of Spawning Chinook Habitat: Similarities and Differences Across the Four River Basins

Three controls on the spatial structure of Chinook spawning habitat were evaluated in the lower segments of the Snoqualmie, Skykomish, Green, and Cedar rivers: geomorphically significant tributary confluences, canyon mouths (i.e., transitions to wide floodplain river segments), and landslides. Although other factors control the spatial structure of riverine habitats, including river meanders and bedrock outcrops, our reliance on remote sensed data (DEMs and aerial photographs) precluded the evaluation of smaller scale features.

A river network model (ESI 2002) predicted the locations of canyons and unconstrained floodplain segments that were surmised to influence the spatial structure of Chinook spawning habitats. All rivers with the exception of the Snoqualmie contained significant bedrock canyons.

A network model in conjunction with a logistic regression equation was used to predict the location of geomorphically significant tributary confluences that could potentially influence river habitats (at the junction). All rivers but the Cedar were predicted to have significant confluence effects that should influence the large-scale organization of Chinook spawning habitats. Overall, the Skykomish, Snoqualmie, and Green rivers were predicted to have a spatial structure of Chinook spawning habitat (i.e., distance between large habitat patches) of 11 to 15 km, 7 km, and 6 km, respectively. The Cedar River was predicted to have a concentration of habitat near the canyon at RM 18.6 in conjunction with streamside landslide sources of gravel. No doubt all river systems have smaller scales of organization controlled by meander wavelength, log jams, and perhaps side channels, but this was not evaluated during this study.

In general, the variation in distance between habitat patches increased with river basin size. The largest separation distance between habitat patches was predicted to be 10 to 30 km in the Skykomish (2000 km^2 drainage area) compared to 6 to 7 km for the Snoqualmie (1,600 km^2) and

Green River systems (1,000 km^2). Distance between tributaries of increasing size downstream in a river basin (i.e., tributaries must increase in size downstream to affect the morphology of rivers of increasing size) is predicted to increase downstream based on the laws of network geometry. This is particularly true in dendritic networks within oval shaped basins (Benda et al. accepted).

Habitat patch size could not be independently predicted using the network model; therefore, other data were used to estimate patch size. For example, the substrate size data in the Snoqualmie River (Booth et al. 1991) indicate that habitat patch size is on the order of 5 mi (8 km), dictated by the spacing between significant confluences and sediment transport mechanics in the river. In the Green River, the length of areas prone to high rates of river meandering (indicating extensive gravel deposits and other types of riverine habitats) is 1 to 3 mi (1.6 to 5 km). Also, gravel patches observed downstream of landslides in the Green River gorge were on the order of 1 to 2 mi long (1.6 to 3.2 km). The size of large scale habitat patches associated with confluences and transitions between canyons and unconstrained floodplain segments found in the four Puget Sound rivers is consistent with other data throughout the western United States and Canada (Chapter 2, Figure 3).

IDENTIFYING THE TEMPORAL STRUCTURE OF RIVERINE HABITATS

The temporal structure refers to the type, frequency, and magnitude of fluctuations in the supply and transport of water, sediment, and wood that can influence the formation of riverine habitats, including channel gradients, substrate size, channel width, floodplain width, side channels, log jams, and hyporheic flow. Frequency and magnitude of channelized disturbances scale with basin size and are influenced by the specific topography, network geometry, basin size, and climate of each basin (Chapter 2, Figure 14). In addition, channel disturbances such as floods and accelerated sediment supply are magnified at topographic knick points in rivers, including in the vicinity of confluences, canyons, and landslides (Chapter 2, Figure 13).

A detailed analysis of the temporal structure of Chinook spawning habitats in the lower portions of the Skykomish, Snoqualmie, Green, and Cedar rivers is beyond the scope of this analysis. Nevertheless, there is information on some aspects of the temporal structure of spawning Chinook habitats in Puget Sound rivers. For instance, the highest rates of channel changes due to flooding and increased sediment supply and deposition are documented to occur in the vicinity of confluences in the Green River (Perkins 2000), pointing to the role of disturbances in creating habitats at those locations. In addition, landslides are contributing to spawning gravels in the Green and Cedar rivers and represent a form of localized watershed disturbance, providing evidence on the role of erosion in creating spawning habitats in those basins.

Habitat patch size associated with confluences, landslides, and canyons can increase or decrease over time in response to watershed-scale disturbances such as widespread storms and floods. For example, during increased flooding and erosion, patch size can increase, although floods and accelerated sediment transport may scour a higher proportion of redds and lead to temporary losses of fish and their habitat. This aspect of the temporal structure cannot be determined from the available data.

CHINOOK SALMON SPATIAL PATTERNS OF SPAWNING AND ASSOCIATION WITH RIVERINE FEATURES

Spatial patterns of Chinook salmon redd abundance were highly variable and non-uniformly distributed within the mainstem study reaches of all four rivers (Figures 17 to 20). Patterns of redd abundance are distinctly different within each river but are generally consistent over time. This is evident from the large variability in SRD among segments compared to the generally low variability of SRD within segments. The temporal consistency of redd spatial distribution is clearly evident in the Snoqualmie and Skykomish rivers, where we have the longest data record. The spatial distribution of redds also varied little over time even though the total population of redds was highly variable over the period of record for three of the four rivers (Figure 21).

The number and size of spawning patches that were discernable at the segment scale generally varied with river basin size. Spawning patches with high SRD were less frequent and were longer in the larger rivers than in the smaller rivers (Table 2). In the Skykomish and Snoqualmie rivers, distinct spawning patches were approximately 6 mi (10 km) to 14 mi (23 km) apart and ranged from approximately 2 mi (3 km) to 8 mi (13 km) long (Figures 17 and 18). In the smaller Cedar and Green rivers, all but one of the spawning patches were 2 mi (3 km) to 4 mi (6 km) apart and ranged from 0.1 mi (0.2 km) to 2 mi (3 km) long (Figures 19 and 20). Patch lengths and inter-patch distances were difficult to delineate given the large survey segments in the Skykomish and Snoqualmie rivers; therefore, these estimates are only approximate. For example, the patch located within the segment at RM 35.7 to 43.6 in the Skykomish River is probably not as long as the segment length (i.e., 7.9 mi). This segment includes the lower portion of the canyon, which probably has poor spawning habitat, as indicated by the low SRD in the upstream canyon segment (RM 43.6 to 49.6, Figure 17). Based on this, we suspect a spawning patch occurs downstream of the canyon but upstream of the Wallace River and is no more than 6 mi long (i.e., distance between the Wallace River at RM 36 and the canyon mouth at RM 42). The estimates of patch lengths in the Snoqualmie River, however, are probably accurate because the substrate particle size data for the mainstem (Figure 7) clearly shows that spawning gravel does not exist outside of the two patches that are delineated by the redd density data. This is why we assume the trend for SRD in the Snoqualmie River goes to zero for the river zone that occurs in between the spawning patches (Figure 18b).

Patch length and inter-patch distances are influenced by the presence of fish barriers and by canyons. Survey segments in the Skykomish and Green rivers that were located below fish barriers (i.e., diversion dams and waterfalls) and were upstream of long canyon reaches tended to have short patches with high SRDs. We did not see this pattern in the Snoqualmie River, where there is no canyon, or in the Cedar River, where the canyon reach is relatively short. However, spawning patches occur downstream of the canyon mouth in all three rivers with a canyon. Where spawning patches also occur upstream of the canyon (i.e., Skykomish and Green rivers), the distance between spawning patches is influenced by canyon length.

Spatial patterns of redd abundance vary with distance from river features. Plots of SRD as a function of distance from the nearest river feature indicate that SRD declines with increasing distance from river features (Figure 22). The declining trend in SRD is not linear with distance and tends to drop off when distances exceed about 2 mi (3.2 km). To evaluate whether